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Char oxidation of torrefied biomass at high temperatures and high heating rates

Jun Li^{a,*}, Giorgio Bonvicini^b, Xiaolei Zhang^c, Weihong Yang^a
Leonardo Tognotti^{b,d}

^a Division of Energy and Furnace Technology, Royal Institute of Technology (KTH), Brinellvägen 23, 10044 Stockholm, Sweden

^b International Flame Research Foundation (IFRF), Via Salvatore Orlando 5, 57123 Livorno, Italy

^c University of Alberta, Edmonton, Alberta T6G 2G8, Canada

^d Dipartimento di Ingegneria Civile e Industriale, Università di Pisa, Via Diotisalvi 2, 56100 Pisa, Italy

Abstract

The char oxidation of a torrefied biomass and its parent material was carried out in an isothermal plug flow reactor (IPFR), which is able to rapidly heat the biomass particles to a maximum temperature of 1400°C at a heating rate of 10⁴ °C/s, similar to the real conditions found in power plant furnaces. During each char oxidation test, the residues of biomass particles were collected and analyzed to determine the weight loss based on the ash tracer method. According to the experimental results, it can be concluded that chars produced from a torrefied biomass are less reactive than the ones produced, under the same conditions, from its raw material. The apparent kinetics of the torrefied biomass and its parent material are determined by minimizing the difference between the modeled and the experimental results. The predicted weight loss during char oxidation, using the determined kinetics, agrees well with experimental results.

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1. Introduction

Biomass is expected to play a major role, in the near future, to substitute fossil fuels, because of its renewability and CO₂ neutrality [1]. The most relevant barriers to its large-scale diffusion are connected to its physical and chemical properties, such as high moisture content, high content of volatiles, low bulk density [2]. Among the available pre-treatment technologies, torrefaction is one of the promising options to upgrade biomass properties [3-4].

* Corresponding author. Tel.: +46 8 790 8458; fax: +46 8 20 7681.

E-mail address: jun2@kth.se.

Nomenclature

ash	ash content of the fuel or char [% _{dry}]
D	oxygen diffusion coefficient [kg/m ² s]
k	chemical kinetic constant [s ⁻¹]
m	mass [kg]
n	oxygen reaction order [-]
P	pressure [Pa]
S	char specific surface [m ² /kg]
X	char conversion [-]
Subscripts:	
0	initial
bd	by difference
P	char particle
O ₂	oxygen
∞	bulk gas

The standard characterization of solid fuels is conventionally performed at relatively low temperatures (<1000°C) and heating rate (<1°C/s). Differently, when the biomass particles enter a pulverized fuel flame, they are quickly heated to a final temperature of about 1400–1600°C at a rate around 10⁴°C /s. Consequently, there is a general lack of quantitative information on biomass char combustion at real combustion conditions, which are necessary to make predictions about thermal conversion, heat transfer and pollutants formation.

Recently, several studies have focused on biomass devolatilization at high temperatures and heating rates. Among these, Biagini et al. developed a method to study the morphology of biofuels after rapid devolatilization as well as the reactivity of their chars. In particular, these were found to be more reactive than the ones produced in milder conditions [5]. However, only a few studies have focused on biomass char combustion. Among these, Jiménez et al. performed a complete set of experiments on a biomass using an entrained flow reactor, and derived reliable kinetic parameters [6].

In this work, the combustion of chars produced from a raw biomass and its torrefied material are studied experimentally in an isothermal plug flow reactor (IPFR), the kinetic parameters are derived, and the effects of torrefaction on char combustion rate are discussed.

2. Char production and oxidation experiments

The characterization experiments were performed on a raw palm kernel shell (PKS) and its torrefied material. This material was produced in a horizontal rotary furnace at 300°C for 30 minutes, in order to achieve a torrefaction degree of about 30%. The torrefaction degree is defined as ratio of the released volatiles and the initial volatile content of the raw biomass material on dry-ash-free basis.

The experiments were carried out in an isothermal plug flow reactor (IPFR), which is a 4 m long drop-tube reactor used to characterize solid fuels under conditions similar to those of real combustion applications, with heating rates around 10⁴ °C/s, and a maximum temperature of 1400°C. A detailed description of the IPFR was given by Bonvicini [7].

In this study, char was produced in the IPFR at 900°C, under an almost oxygen-free atmosphere (oxygen below 0.5%), with a residence time of 300 ms, in order to complete the devolatilization but prevent the graphitization of the carbonaceous matrix. The results of a standard characterization of the produced chars and their parent materials and are shown in Table 1.

Table 1. Standard characterization of the parent biomasses and their chars

Biomass or char	VM [% _{dry}]	FC [% _{dry,bd}]	ASH [% _{dry}]	C [% _{dry}]	H [% _{dry}]	N [% _{dry}]	O [% _{dry,bd}]
Raw PKS	72.78	22.99	4.23	50.90	5.27	0.40	39.20
Torrefied PKS	49.92	41.58	8.50	60.67	4.33	0.57	25.93
Raw PKS – char	21,44	62,19	16,38	53,60	2,25	0,60	27,17
Torrefied PKS – char	16,27	68,59	15,14	67,54	2,53	0,62	14,17

To fully understand the effects of biomass torrefaction on char combustion, a total of 24 tests were carried out with different chars, temperatures (900-1200°C), residence times (0-600 ms) and oxygen concentrations (3-9%). During every char combustion test, the partially burnt particles were collected and then analyzed to determine the value of mass conversion according to the ash tracer method. This method, described by Equation (1), assumes the ash content of the biomass to be inert and thermally stable.

$$X = 1 - \frac{Ash_0}{Ash} \left(\frac{1 - Ash}{1 - Ash_0} \right) \quad (1)$$

Figure 1 shows the trends of conversion measured during char combustion tests performed at 900°C on the raw and the torrefied PKS as a function of the residence time and the oxygen concentration. It can be noted that, an increase of the oxygen concentration in the bulk gas leads to a faster conversion. Moreover, the char produced from raw PKS is more reactive than the one produced from the torrefied one. For example, combustion of torrefied biomass char with 9% oxygen gives almost the same conversion of raw biomass char burnt with 4% oxygen.

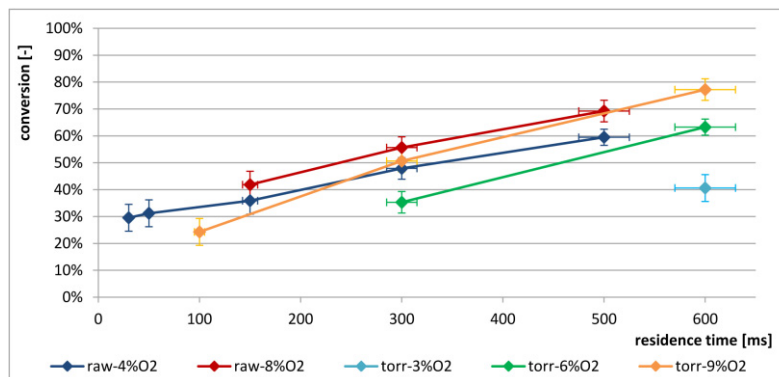


Figure 1. Conversion trends versus residence time and oxygen concentration for raw and torrefied PKS, at 900°C

3. Char combustion kinetics

The model used to describe char conversion during combustion tests performed in the IPFR takes into account both the chemical kinetics and the external diffusion of oxygen. The evolution of the char particle size during combustion is also considered. A detailed description of the kinetic model was given by

Karlström [8], whereas its main formulation is expressed by Equation (2).

$$\frac{dm_p}{dt} = S_p k \left(P_{O_2, \infty} - \frac{dm_p}{dt} \frac{1}{S_p D} \right)^n \quad (2)$$

In this study, the kinetic parameters were determined, for each of the two materials, by minimizing the root square mean error between the modeled and the experimental values of conversion.

The predictions of weight loss of chars, using the optimized kinetics shown in Table 2, are in good agreement with the experimental results. In fact, the values of activation energy, pre-exponential factor and reaction order lead to a lower reactivity for the torrefied PKS compared to its raw material, which was also observed during the experimental tests.

Table 2. Char combustion kinetic parameters

Biomass char	A [kg/m ² sPa ⁿ]	E [kJ/mol]	n [-]	RSME [%]
Raw PKS	0.3900	47.5	0.29	8.60
Torrefied PKS	0.0037	60.0	0.80	4.50

4. Conclusions

In this study, the combustion of chars produced from a torrefied biomass and its parent material (PKS) was investigated in an Isothermal Plug Flow Reactor with temperatures between 900 and 1200°C and oxygen concentrations between 4 and 9%. According to the experimental results, it can be concluded that chars produced from a torrefied biomass are less reactive than the ones produced, under the same conditions, from its raw material. Also the kinetic parameters, derived according to a chemical-diffusion model, agree with these conclusions.

Acknowledgements

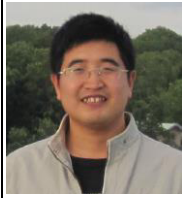
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Biography

Jun Li is a Ph.D. in Division of Energy and Furnace Technology at KTH Royal Institute of Technology, Sweden. His PhD project is to develop a co-firing method for 100% fuel switch in coal-fired boilers. Currently, his researches focus on the biomass combustion, co-firing, torrefaction, and CO₂ and NO_x reductions.